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Temporal variation of stable isotopes in a precipitation-groundwater system: implications for determining the mechanism of groundwater recharge in high mountain-hills of the Loess Plateau, China

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Abstract

The groundwater in shallow loess aquifers in high mountain-hills in the western Loess Plateau in China is almost the sole water resource for local residents. However, the question about how the loess groundwater naturally circulates in these high mountain-hills, characterized by low precipitation and high potential evaporation, remains unclear. The objectives of this study are to evaluate the application of hydrogen and oxygen isotopes to (1) examine temporal variations of the isotopic composition of precipitation and shallow groundwater and (2) uncover the mechanism of groundwater recharge in high mountain-hills. Results from 2 years of monitoring data show a difference in the stable isotopes for groundwater and local precipitation between the winter and summer periods. Similar to precipitation, stable isotopes in groundwater are observed to be depleted in winter and enriched in summer, particularly in oxygen isotope. A prominent characteristic is that H and O isotopes of groundwater show a very clear response to strong precipitation in the rainy season in 2013. The results highlight that local precipitation is the likely recharge source for groundwater in shallow loess aquifers. Annual recharge from local precipitation maintains the groundwater resource in the shallower loess aquifer. The mechanisms governing shallow loess groundwater recharge in high mountain-hills were evaluated. In addition to possible vertical slow percolation of soil water through the unsaturated zone, rapid groundwater recharge mechanisms have been identified as temporal preferential infiltration through sinkholes, slip surface or landslide surface and through the interface of loess layer and palaeo-soils. Most groundwater can be recharged after a heavy rainy season.

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Temporal variation of stable isotopes in a precipitation-groundwater system: implications for determining the mechanism of groundwater recharge in high mountain-hills of the Loess Plateau, China

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Running head: Mechanism of groundwater recharge in loess aquifer

ABSTRACT

The groundwater in shallow loess aquifers in high mountain-hills in the western Loess Plateau in China is almost the sole water resource for local residents. However, the question about how the loess groundwater naturally circulates in these high mountain-hills, characterized by low precipitation and high potential evaporation, remains unclear. The objectives of this study are to evaluate the application of hydrogen and oxygen isotopes to (1) examine seasonal variations of the isotopic composition of precipitation and shallow groundwater, and (2) uncover the mechanism of groundwater recharge in high mountain-hills. Results from two-years of monitoring data show a difference in the stable isotopes for groundwater and local precipitation between the winter and summer periods. Similar to precipitation, stable isotopes in groundwater are observed to be depleted in winter and enriched in summer, particularly in oxygen isotope. A prominent characteristic is that H and O isotopes of groundwater show a very clear response to strong precipitation in the rainy season in 2013. The results highlight that local precipitation is the only possible recharge source for groundwater in shallow loess aquifers. Seasonal or annual recharge from local precipitation maintains the groundwater resource in the shallower loess aquifer. The mechanisms governing shallow loess groundwater recharge in high mountain-hills were evaluated. In addition to possible vertical slow percolation of soil water through the unsaturated zone, rapid groundwater recharge mechanisms have been identified as seasonal preferential infiltration through sinkholes, slip surface or landslide surface， and through the interface of loess layer and palaeo-soils. Most groundwater can be recharged after a heavy rainy season.

Key words: Groundwater recharge; Hydrogen and oxygen isotopes; Seasonal recharge; High mountain-hills; Loess Plateau

1. INTRODUCTION

High mountain-hills in the Loess Plateau are part of the Liupanshan Mountains and

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its western area with an average altitude over 1500 m a.b.s. (Fig. 1). The region is in what is typically a warm-temperate arid climatic zone with generally less than 500 mm in annual average precipitation but over 1000 mm in potential evaporation. There are several rivers flowing at the base of hills and occasionally small springs seep from valleys. It is, however, impractical to pipe and pump these surface water resources to hills due to high costs and the quantity is limited. This means that precipitation and soil water are essential for maintaining agriculture and forestry development. Local residents are completely dependent on weather conditions, having their annual basic living water demands met by wells and springs. To date, groundwater flow paths and circulation is unknown in these high mountain-hills. The relatively impermeable nature of the fine texture characterizing the thick loess on these high mountains makes it difficult for local precipitation to percolate through the thick loess to recharge deeper groundwater in conditions of low precipitation and high potential evaporation. However, except for local precipitation, there seems to be no other recharge source for this groundwater system. With challenges of climate and land-use changes in the future, it is therefore essential to determine the recharge source, movement and residence of groundwater, and understand the mechanism of groundwater recharge in the loess aquifer. This would provide the basic information for assisting local residents to manage their water resources in a sustainable way for the future. It would also assist local government to establish mountain immigration policy and optimize land-use change options.

Fig .1

Some environmental isotopes of hydrogen and oxygen have been widely used in hydrologic studies due to their conservative characteristic of moving with the H_2O molecule (Kendall and McDonnell, 1998; Willem, 2006). As such, by measuring the stable isotopic ratios of δ^2H and $\delta^{18}O$ in precipitation, soil water and groundwater, it is possible to trace the regional water circulation and mixing between end member components to uncover information about a number of hydrological processes, including the proportion of precipitation, infiltration, evaporation, and transpiration (Allison, 1988; Turner et al., 1991; Bradd, 1993, 2004; Kendall and McDonnell, 1998; Gat, 2010).

Limited isotopic studies have been performed in the Loess Plateau, focusing mainly on the large loess tablelands and platforms in Shanxi and eastern Liupanshan Mountains. Until now, how surface water infiltrate through unsaturated soil zone to recharge groundwater has been under dispute for a number of decades. A number of studies documenting tracer movement in the soil column have pointed to the existence of preferential fluid flow through vertical fissures, macropores, cracks, decayed plant roots, and earthworm burrows to rapidly recharge groundwater (Roy and David, 1969; Yan and Wang, 1983;Van Ommen et al., 1989; Komor and Emerson, 1994; Ritsema et al., 1997; Gehrels et al., 1998; Ritsema and Dekker, 1998; Vincent et al., 2001; Gates et al., 2011; Yasuda et al., 2013). Rainfall infiltration has also been assumed to be more like a piston infiltration mode to slowly percolate downward and recharge groundwater (Qu, 1991； Yan, 1986; Zhang et al., 1990; Lin and Wei, 2006; Huang et al., 2013) or piston flow and preferential flow to recharge groundwater may be simultaneously present in the loess aquifer (Gazis and Feng, 2004; Liu et al., 2010, 2011; Xu et al., 2010). Some studies conclude that the depleted isotopic signature of loess groundwater may be also consistent with isotopic compositions of palaeo-waters in northern China, where the groundwater may have been recharged during glacial-interglacial transitional periods (Currell et al., 2010; Gates et al., 2008; Chen et al., 2003; Liu et al., 2010). In contrast, considering there is limited precipitation but very high potential evaporation and significantly more enriched average isotopic composition of local precipitation than those of groundwaters in the Loess Plateau, Chen et al. (2004 and 2012) commented that the main recharge source is not the local precipitation but from deep regional confined groundwater systems discharging upward from far mountainous sources. This situation may be possibly occurred in large loess tablelands and platforms or some artesian basins.

From these contrasting models above presented in recent decades, it can be seen that the mechanism of groundwater recharge in loess remains unclear. In particular, previous studies mainly focus on the wide tableland or platform at the lower altitude with higher annual precipitation in the Loess Plateau. However, few studies in the high mountain-hills of the Loess Plateau, and in particular very few studies in the more arid area of western Liupanshan Mountains have been performed, where the mechanism of loess groundwater recharge seems to remain unsolved.

Thus, this paper aims to improve our understanding of the groundwater recharge in high mountain-hills of the Loess Plateau. The objectives of this study are to (1) examine seasonal variations of the isotopic composition of precipitation and shallow groundwater, and (2) uncover the mechanism of groundwater recharge in high mountain-hills.

2. STUDY SITES AND METHODS

The geomorphology of the study area of high loess mountain-hills distributed between the western Liupan Mountains and Eastern Huajia Mountains is characterized by thick loess deposits with steeply incised valleys and rolling hills (Fig. 1). The deposits of hills are mainly covered by the Upper Pleistocene Malan Loess and Middle Pleistocene Lishi Loess (Fig. 2). The thickness of the loess strata is generally over 30 meters with a range from 30 to 200 meters. There are several interlayers of palaeo-soils developed between the loess strata. Their thickness ranges from less than 1 meter to over 3 meters. Groundwater resides in both the crests and depressions of the hills. Generally, groundwater flows parallel with the direction of the valley and springs appear in the heads of valleys. The shallow groundwater primarily exists in porous sediments. Aquifers are comprised mainly of silty loess materials and always located above the interface of loess and palaeo-soils or red clay. The thick red clay strata (from 30 to 60 meters in thickness) that underlies the loess acts as an excellent aquiclude and the palaeo-soils inter-bedded the loess strata generally acts as an aquitard. The underlying bed rock is generally the sand rocks of the late Paleogene Period to Neogene Period. There is no evidence of deep confined groundwater under the loess strata discharging to the surface in the high maintain-hills. Surface overland runoff is only developed in some valleys with small amount of water from springs or intense storm events occurred in summer. Generally, precipitation is dominated by summer rainfall and snowfall seems to be not significant in the hydrologic budget. Even in the wet year of 2013, there was only one occurrence of snow in small quantity at Xiegou (6.5mm) and two times at Longchuan (5mm and 6.5mm). With respect to 2013, it snowed harder in the early 2014 from January to March in Longchuan. However, the total amount of snow was only less than 60mm and accounted for less than 10 percent of annual total precipitation (585mm) in 2014.

Fig. 2

Six field sites located on the high hills of Loess Plateau were selected as long-term monitoring stations for this study, namely Xiegou (XG), Macha (MC), Longchuan (LC), Longshan (LS), Yangwan (YW), and Wangping (WP) as displayed in Figure 1. These sites were selected because they have a perennial shallow groundwater system as part of the loess aquifer. The basic characteristics of hydrology, geography and climate are summarized in Table 1. At these sites, groundwater levels range from 8 m to 30 m in depth below surface. Groundwater samples were mainly collected from wells (or bore holes) used by local residents. That is to say, the water in the wells is always fresh groundwater from the loess aquifers. Groundwater samples were collected on the early days of the month (before 5th). Due to the low permeability of the loess aquifer, before sampling every time, water was pumped to nearly dry and then a fresh sample was collected after 24 hours. As an arid area with high potential evaporation, low precipitation is unlikely to infiltrate to recharge the deeper groundwater. Hence, only the larger precipitation with runoff occurring observed on the ground (generally larger than 5mm) was sampled for two years (from November 2012 to November 2014). Rainwater was collected with a large cup (1 litre) when precipitation events would occur. 10 ml water samples were abstracted from the cup and transferred to a small plastic bottle as soon as possible when each precipitation event looks likely to stop. Snow samples were collected in plastic salvers and allowed to melt indoors under natural room temperature. During sampling, storage and transportation procedures, the primary task is to prevent the sample from evaporating. Hence, all water samples were tightly sealed in thick plastic bottles and preserved in a refrigerator or farmer's cellars until analysed. Some precipitation events and monthly groundwater samples were not collected due to practical constraints, except for the Longchuan site, where almost all larger precipitation events and monthly groundwater samples were successfully obtained.

Table 1

Stable isotopic measurements were performed at the State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering, Hohai University. The water sample was directly injected into the Mat 253 mass spectrometry by a micro-pump and used a continuous flow method for determination of H and O isotopic compositions. This technique involves reduction of H_2O by reaction with glassy carbon in a sample injection system at high temperatures. H_2 and CO are produced by reaction with the carbon at 1450℃ in a helium carrier gas. Product gases are separated in a gas chromatograph and analyzed in a mass spectrometer configured to make oxygen and hydrogen isotope analyses in a continuous flow mode. The results are reported relative to SMOW with a standard deviation of ±1‰ and ± 0.20‰, respectively. All sampling sites and distributions are shown in Fig. 1, and the isotope data are reported in Table 2 and 3, respectively.

Table 2

Table 3

3. RESULTS

3.1. STABLE ISOTOPIC COMPOSITION OF PRECIPITATION

Spatial-temporal variations of the amount of precipitation in high mountain-hills of the Loess Plateau are large. However, the spatial variations during the heavy rainy season from May to September are relatively small. According to records from two weather stations, Pingliang in the east, and Jingning in the west Liupan Mountains, total precipitation from May to September 2013 is found to be 87.4 percent and 87.1 percent of annual precipitation, respectively. Significantly, the precipitation during the rainy season in 2013 was the highest observed over the past several decades; the total rainfall between May and September 2013 was approximately 40 percent higher than the average for the past 30 years. Records from weather stations show that the annual total precipitations are 760 mm in Pingliang and 670.4 mm in Jingning in 2013, which are higher 31.4 percent and 30.5 percent than that of the average total values (480 mm in Pingliang and 466.3 mm in Jingning) in past 30 years (Fig. 3). In addition, the heavier storm events occur simultaneously at the different monitoring sites within the research area. Conversely, in the arid winter season, which is from October to April in the following year, rain events are mainly sporadic in nature and characteristically small rain or occasionally snow events. Monthly precipitation and temperature fluctuate and trend together. The temperature is high from May to September and the highest in July. Correspondingly, precipitation is also high during this period where maximum occurs in July 2013 and in September 2014. This is typical of a monsoon climate that is found in the Loess Plateau. In the summer season, the climate is typically moist with higher temperature affected by warm-moist currents from the ocean, while in winter it becomes arid and cold affected by continental dry-cold currents.

Fig. 3

With respect to precipitation, the hydrogen and oxygen isotopic compositions of precipitation also show great variations with a range from -166.5 ‰ to 19.3 ‰ in δ^2H and -22.13 ‰ to 1.51 ‰ in δ^{18}O and a large standard deviation according to data from four key monitoring sites of Xiegou, Longchuan, Longshan and Yangwan (Table 2). Precipitation samples were incomplete at Xiegou, Yangwan and Longshan. Only the Longchuan, where most of the precipitation samples were collected, can be considered representative monitoring site. From the seasonal variation of monthly mean δ^2H, δ^{18}O and d values (Table 2, Fig. 4a and c and Fig. 5a), the δ^2H and δ^2O isotopes and d values exemplify seasonal variation. In winter season before May 2013 (sampled from November 2012 to April 2013), the mean δ^2H and δ^{18}O values of precipitation show more negative values than that in the summer season (from May to August 2013). The d values show fluctuations with seasonal changes, where they show lower values in summer while higher values in winter (Table 2； Fig. 5a). In particular, a very prominent peak of δ^2H and δ^{18}O and valley of d value appear on the curves of Figure 4 (a, c) and 5a, which is well corresponding to heavy precipitation from May to August 2013. From October 2013 to April 2014, the δ^2H and δ^{18}O roughly shows declined and d shows increased trends. With respect to heavy precipitation in rainy season in 2013, there are less prominent peaks in δ^2H and δ^{18}O from May to August 2014 like in 2013 due to lower precipitation, but higher δ^2H and δ^{18}O and lower d values from May to August 2014 can be roughly identified. As a whole, the seasonal fluctuation characteristics of H and O isotopic distribution of precipitation in the Loess Plateau are consistent with other recorded localities in the world (Clark and Fritz，1997；Gazis and Feng, 2004).

Fig. 4

Fig. 5

3.2. STABLE ISOTOPIC COMPOSITION OF GROUNDWATER

With respect to precipitation, the monthly stable isotope data in groundwater over the two-year monitoring period show that the range of values is not as large as precipitation events. However, there is an observed difference between winter and summer values. Similar to precipitation, stable isotopes are found to be depleted in winter while enriched in summer, particularly in $\delta^{18}O$ values (Table 3 and Fig. 4). The stable isotopes of the groundwater from the areas of Longchuan, Longshan, Yangwan and Macha show a larger range of variation than that observed at Xiegou and Wangping. The latter two sites only display larger difference between summer and winter seasons. The monthly composition of stable isotopes in groundwater within the monitoring period from November 2012 to November 2014 shows the largest standard deviation in the Longchuan monitoring borehole and smallest in Xiegou well (Table 3). In particular, the stable isotopic composition for groundwater in the Longchuan monitoring borehole for an average annual period that includes average winter period (October 2012 to April 2013) and a summer period (May 2013 to September 2013), are -72.0‰ and -63.6.0 ‰ in δ^2H and -10.20 ‰ and -6.87 ‰ in $\delta^{18}O$ values respectively (Table 3). In contrast, the average winter period and a summer period in 2014 are -67.4 and -67.7 ‰ in δ^2H values and -7.60 ‰ and -9.30 ‰ in $\delta^{18}O$ values respectively. Stable isotope values in groundwater do not vary much spatially between different areas compared to the precipitation in the area. For example, the average isotopic composition of groundwater during the two-year monitoring period at Xiegou is (-71.1 ‰ in δ^2H and -9.45 ‰ in $\delta^{18}O$) in the eastern Liupan Mountains and in western Liupan Mountain monitoring sites, variations are not high, as seen in the data for Longchuan (-67.9 ‰ in δ^2H and -8.52 ‰ in $\delta^{18}O$), Longshan (-75.9 ‰ in δ^2H and -9.68 ‰ in $\delta^{18}O$) and Yangwan (-65.1‰ in δ^2H and -8.83‰ in $\delta^{18}O$) (Table 3).

4. DISCUSSION

4.1. SEASONAL FLUCTUATIONS OF GROUNDWATER TABLE

Local residents extract groundwater from most monitoring wells every day for their domestic needs. This is problematic for interpreting groundwater level fluctuations in these wells. According to borehole observations in Longchuan and Yangwan and discussions with residents, it can be concluded that the water yield of many springs or wells in high mountain-hills of the Loess Plateau decreases, and subsequent lowering of the water table occurs after a long arid period of at least several months from the end of winter to early summer. Some wells dry up completely in very arid seasons. In the rainy season and early winter, particularly after heavy rains from July to September, groundwater levels recover in these wells. For example, the water table and amount of water yield observed increased greatly in November 2013 in Longchuan borehole and Yangwan well after summer heavy rainfall. Correspondingly, the seasonal trends of δ^2H and δ^{18}O values show unusual fluctuation with higher values during May to September 2013, and lasting until April 2014 (Fig 5b and d). Generally, wells with larger seasonal variation of stable isotopes in groundwater will show larger groundwater level fluctuations. In contrast, the groundwater levels are relatively stable in wells at Xiegou and Wangping. In these locations, even during a very arid or wet year, well yields and water table relatively remain constant and stable isotopic compositions show a smaller seasonal variation.

4.2. GROUNDWATER RESPONSE TO PRECIPITATION BASED ON STABLE ISOTOPE ANALYSIS

Monthly groundwater and precipitation samples for a representative site at the Longchuan were plotted as a δ^2H and δ^{18}O relationship (Fig. 6). Here Longchuan was selected to be a representative monitoring site for almost all the larger precipitation samples that were collected. With respect to the Global Meteoric Water Line (GMWL), the regression line for precipitation from Longchuan is slightly lower than that of GMWL (8.0). Its regression equation is $\delta^2H=7.40\times\delta^{18}O-0.12$ (Fig .6). Lower regional atmospheric moisture content and higher evaporation inland of the Loess Plateau is an explanation for the lower slope of the local meteoric water lines (LMWL).

Fig. 6

It is observed that from the δ^2H and δ^{18}O plots for these groundwater samples, which most are located on or very close to the LMWL, but some samples slightly deviate from the LMWL (Fig. 6). These samples are not limited to the summer season and some of them are collected from winter, which indicate that different amount or modes of precipitation and infiltration should cause different intensities of evaporation during precipitation and infiltration. According to Huang et al., (2007), the depth of the evaporation limit for groundwater is about 4.5-6.3 m for bare or winter wheat lands in the Loess Plateau. The water table across the study area generally exceeds 10 m in depth from the surface (Table 1). In addition, the samples were mainly collected from fresh water seeps from aquifers. Thus, the evaporation effect causing isotopic fractionation from the groundwater table should be negligible. It can therefore be concluded that the seasonal fluctuations of stable isotopes in groundwater is dominated by ongoing replenishment of recharge water with different isotopic compositions. Most wells display enriched stable isotopes occasionally in winter due to the lag effect of summer recharge events. For example, there are no obvious precipitation events with enriched isotopes occurring in winter from November 2013 to April 2014 except for one small snow event that occurred in Longshan in January 2014. As a whole, the δ^2H and $\delta^{18}O$ values of most groundwater samples are limited to the mid-range of local precipitation.

Generally, rainfall always shows obviously seasonal variations in the stable oxygen and hydrogen isotopic composition observed by many previous studies (Jouzel et al., 1997; Lee et al., 2003; Kabeya et al., 2007). Liu et al. (2011) concluded that the spatio-temporal variations of precipitation isotopic compositions in the Loess Plateau are dominated by the difference in water vapor origin, monsoon intensity and hydrological processes. As indicated from the diagrams of monthly variation of δ^2H and $\delta^{18}O$ (Fig. 4a and c), the isotopes of precipitation in high mountain-hills of the Loess Plateau also show regular seasonal variations. As a whole, the $\delta^{18}O$ show relatively lower values in winter and higher values from summer. The deuterium excess is used widely to trace the origin of moisture of precipitation and water cycles (Merlivat and Jouzel, 1979). The d-values of precipitation in high mountain-hills of the Loess Plateau also show regular spatial-temporal variations (Fig. 5a). The d-values of precipitation from Longchuan, Longshan and Yangwan show higher values in winter and lower values in summer. Despite a lack of precipitation samples from August to September at Xiegou, the d-values of precipitation are higher before May and lower after June. This seasonal fluctuation of d-values for precipitation suggests that water vapor from precipitation in winter in high mountain-hills of the Loess Plateau mainly originates from inland moisture source or occupies a larger proportion than that in summer (Huang et al., 2015). The higher δ^2H and $\delta^{18}O$ and lower d-values of precipitation in summer from May to September are dominated by stronger evaporation during rainfall as well as by stronger monsoonal character with oceanic vapor origin. Xiegou is located in the eastern Liupan Mountains where the geomorphology is characterized by wide tableland and flat plateaus to the east. Water vapor from the Pacific Ocean travels to this region. Thus, the d-values of rainfall in summer at Xiegou seem to be higher than that in the western areas of Liupan Mountains and appear to be sourced from this oceanic water vapor and have less evaporation. Conversely, Longchuan in the western Liupan Mountains is located in Huajia Mountains and is closer to inland arid desert areas to the west, where the moisture content of atmosphere is relatively lower for an inland moisture source and precipitation always undegoes stronger evaporation. Hence, the rainfall will show enriched δ^2H and $\delta^{18}O$ and depleted d-values in summer, strongly characterized by a higher evaporation component and a less oceanic water vapor source. In particular, these characteristics are more enriched in the summer season of 2013 that had higher rainfall than that in 2014, which had lower rainfall (Fig. 4-5). During the heavy rainy season in 2013, very prominent peaks are observed in the $\delta^{18}O$ values (Fig. 4a).

The seasonal variation trend of $\delta^{18}O$ and d-values of groundwater, as a whole, roughly shows similar variations with local precipitation (Fig. 4-5). The $\delta^{18}O$ values are lower and d-values are higher in winter from November 2012 to April 2013. There is a sudden increase in δ^2H and $\delta^{18}O$ values and decrease in d values from June to September, and again after September 2013. With respect to 2013, the isotopic values of groundwater samples in 2014 show a relatively smaller variation and vary randomly without typical seasonal character. This can be explained by time-lag effects from unusually heavy precipitation in summer 2013 as well as relatively lower precipitation in summer (May to August) 2014. In particular, the summer recharge water with very higher δ^2H and $\delta^{18}O$ values in 2013 possibly restrains the decreasing value trend of groundwater in the winter season in 2014 (October 2013 to April 2014). The variation observed in the monthly isotopic values for local precipitation and groundwater is diluted from the heavy rainfall in 2013. As such, the isotopic variation becomes negligible at the beginning of the rainy season in 2014. It is reasonable to conclude that the regular seasonal variation in isotopic signature observed in groundwater could be caused by seasonal recharging waters. When comparing isotope signatures of monthly precipitation with monthly groundwater, as a whole, the seasonal fluctuation characteristics of $\delta^{18}O$ distribution of groundwater are roughly consistent with local precipitation values. The seasonal variation of δ^2H values of groundwater is although relatively small but a similar response with $\delta^{18}O$ can still be identified.

4.3. **RECHARGE SOURCE OF GROUNDWATER**

Despite the controversy surrounding the origin of groundwater in deep loess aquifers in the flat loess plateau or wide tableland, local precipitation seems to be solely responsible for the groundwater recharge source for the loess aquifer in high mountain-hills when rivers or valleys surrounding them are at elevations lower by several hundred meters. From a hydraulic perspective, it is unlikely that deep circulating confined groundwater could move upward to recharge a shallow phreatic aquifer in the higher mountain-hills. An important reason is that most gullies around the mountain-hills are usually dry. Runoff only occurs after heavy rain or storm events and flows into the gullies. This surface runoff occurs when the infiltration rate of the loess soils is exceeded. As such, it is highly unlikely that deep confined groundwater flows upward through thick red clay (generally 30 to 60 meters in thickness) or palaeo-soils with very low permeability to recharge the shallow loess aquifer in the top or higher location of hills, rather than discharging directly to lower valleys and gullies (Fig. 2).

The variability in stable isotopic composition of groundwater combined with seasonal water table fluctuations is sufficient evidence to indicate that the groundwater in the loess aquifer of high mountain-hills does not originate from the upwelling of ancient regional groundwater. Generally, the deuterium and oxygen-18 isotopic composition of well mixed deeper groundwater systems would be constant and represent a long term mean climate value. There would not be annual seasonal variations observed in these isotopic compositions if the water was sourced from old regionally distant recharged groundwater. In addition, according to a number of researchers, ancient groundwater will show much more depleted isotopic signature than local modern precipitation (Currell et al. 2010; Gates et al. 2008; Chen et al. 2003; Liu et al., 2010).

The data from this study indicates that groundwater in the mountain-hills show marked seasonal variation in oxygen isotopes, particularly the seasonal trend observed in deuterium excess associated with larger precipitation events (Fig. 5). The variations in isotopes in monthly groundwater are definitely limited within the range of local precipitation rather than depleted signatures (Fig. 6). Hence, a conclusion can be made that the groundwater in shallow loess aquifer in high mountain-hills in the western Loess Plateau originates in local precipitation recharge and the seasonal new water replenishes groundwater much more rapidly than expected before.

With respect to seasonal fluctuation of $\delta^{18}O$ values in groundwater, $\delta^{2}H$ values show a smaller variation. This can be described by a mixing model with two end members. In the plot describing the relationship of $\delta^{18}O$ and $\delta^{2}H$ (Fig. 6), groundwater isotopic compositions mostly fall along a line between two end mixing members with: ① old water existing in aquifers from January to February 2013 with average values of $\delta^{18}O$ = -11.21‰ and $\delta^{2}H$ = -74.1‰ (OW13) and ② new recharged precipitation in 2013 with weighted average values of $\delta^{18}O$ = -6.19‰ and $\delta^{2}H$ = -60.2‰ (AMW13). Both the annual average groundwater in 2013 (AGW13), 2014 (AGW14) or two-year's average groundwater (AGW) are just located on the mixing line. Thus, it can be inferred that the average groundwater mainly sources from a mixture of old existing water and new recharge water in the wet year 2013. This relationship and the timing of isotopic change in the groundwater also suggest that the groundwater is more influenced by the heavy precipitation of 2013 than that of 2014. Due to smaller differences of δ^2H values than $\delta^{18}O$ values between the two mixing end members, there displays larger seasonal fluctuation of oxygen-18 isotopic signatures than that of hydrogen isotope in the monthly groundwater.

According to the following equation for isotopic mass balance, the average mixing proportion of two end members during the wet year 2013 can be estimated:

$$f_{(1,2)} \times X_{AMW13} + (1-f) \times X_{OW13} = X_{AGW13}$$

Where $f_{(1,2)}$ denotes the proportion of new water recharge in 2013 calculated by $\delta^{18}O$ (f_1) and δ^2H (f_2), respectively. X_{OW13} denotes the average $\delta^{18}O$ and δ^2H values of groundwater from January to February in 2013 (end member ① in Fig. 6); X_{AMW13} denotes the weighted average $\delta^{18}O$ and δ^2H values of precipitations in the wet year 2013 (end member ② in Fig. 6); X_{AGW13} denotes the annual average groundwater in 2013. Due to the inadequate number of samples for monthly groundwater collection or intense precipitation events in other sites, only Longchuan is selected to calculate the recharge proportion. The previous analysis concluded that the groundwater in 2014 may be affected by the lag-time effect from unusual heavy summer rainfall in 2013 and is not reasonable to be calculated.

The calculation results show that the new recharge proportion of water accounts for about f_1=60.4 and f_2=44.6 percent by $\delta^{18}O$ and δ^2H isotopic values during 2013 in Longchuan. A larger difference of proportion calculated by H and O isotopic values should be probably attributed to evaporation during precipitation and infiltration because evaporation always plays a greater effect on oxygen than the hydrogen isotopes. That is why the most groundwater samples are located to the upper-right area of the meteoric water line. Of course, due to unusual heavy rains in 2013 in recent 30 years, the calculated annual recharge proportion for groundwater may be larger than that in a typical year. However, given that there is around 40 percent annual precipitation recharge of the shallow groundwater in the loess aquifers in high mountain-hills in 2013, this is an indication that annual rapid recharge is expected to occur.

4.4.MECHANISM GOVERNING SHALLOW GROUNDWATER RECHARGE

Most studies show that it is difficult for precipitation to infiltrate through thick loess layers to recharge groundwater where it depends on piston flow under low precipitation and much higher potential evaporation in the surface (Murphy et al., 1996; Chen et al., 2008; Gates et al., 2011; Yasuda et al., 2013). Even if it did occur, the recharge time would be very long and the seasonal isotopic effects will be eliminated or greatly attenuated (Huang et al., 2013). For a relatively shallow loess aquifer at approximately 20m in depth from the surface in high-maintain hills, piston flow may be one of the potential recharge modes. However, nearly or more than 40 percent annual replenishment and seasonal variations of stable isotopic signatures occur in groundwater. It is unlikely that the recharge can be developed by the piston flow to infiltrate and percolate through unsaturated loess zone to recharge. To explain the seasonal variations of deuterium and oxygen-18 isotopes recorded in groundwater, a rapid recharge mechanism needs to be identified that will account for the fluctuations of water table and relatively abundant groundwater in high mountain-hills. This suggests that in addition to the traditional slower piston flow recharge mechanism, those seasonal rapid preferential pathways exist allowing rapid recharge to occur.

Field observations indicate that all kinds of microtopography features exist such as vertical fissures, macro-pore, sinkholes, solution passages or sinks. These can be potential conduits for preferential infiltration flow paths for rapid groundwater recharge in the Loess Plateau. But according to field observations in the Longchuan, Longshan, Macha and Yangwan sites, the most significant and common preferential flow path for recharge in the loess is by infiltration through larger sinkholes, landslide surfaces and the interface between the loess and palaeo-soils or red clay exposed on the top of mountain-hills percolating along the slope above red clay strata (Fig. 2). This is the reason why many springs and wells can be developed at different elevations in this landscape. Generally, the thick red clay, or some interbedding of palaeo-soils develop below or between the loess layers. These can sometimes be exposed at the surface by erosion and denudation. In the high mountain-hills in the western Loess Plateau, the lower part of these strata has variable gradients such as at the Longchuan and Yangwan site. Due to high viscosity and plasticity of the red clay or palaeo-soil layer with fine grains under the loess layer or interbedded in the loess layers, landslides are less prevalent and fissures are rarely developed in the red clay strata. As such this layer can act as an aquiclude in the loess groundwater system. However, the loess layers are looser and have a coarser grain than the red clay or palaeo-soils. A landslide always occurs between the loess layer and red clay or palaeo-soils, causing large fissures to develop in the slip interface surface. Thus, the heavier precipitation on the hill tops will rapidly infiltrate through this interface landslide surface or some larger sinkholes and then percolate laterally along slopes in the relatively loose layer of loess. A groundwater mound can form when the gradient of the aquiclude layer is small.

Due to rapid vertical infiltration of precipitation through the interface or slip surface between loess and the clay layer, precipitation from large events, such as the heavy rainfall events that occurred from May to September 2013, will be sustained in the loess, and potential evaporation is reduced even under arid or semi-arid conditions. However, since the monthly groundwater stable isotope data have relatively smaller variations than that of the precipitation events, and a lag-time exists for the groundwater table to respond to some typical large precipitation events, the recharge mechanism is unlikely to be from vertical preferential flow to directly reach the groundwater table through conduits. At first, the precipitation can infiltrate rapidly from the surface through preferential conduits, and then it would become increasingly slower with a low gradient for the aquiclude strata that laterally percolates to recharge groundwater. Thus event precipitation cannot vertically reach the groundwater table directly at once within a short time. The stable isotopes of every precipitation event will be gradually attenuated during diffusional redistribution and mixing with old or antecedent water existing in aquifers. So, it cannot be simultaneously identified in both the isotopic records of each precipitation event and from groundwater responses within a short period even after one time of heavy precipitation.

From the field observation, the groundwater level is shallower (about 10-12 m in depth from the land surface) in Longchuan section (Fig. 2). There are many small perennial springs discharging groundwater in lower valleys causing the exchange proportion of new recharge water and old existing water to increase significantly. Corresponding to this, the stable isotopes of groundwater display larger seasonal variations than that in adjacent area of Longshan. Despite not being able to calculate the relative proportions at the Yangwan site due to inadequate isotopic data, it may be comparable with Longchuan based on similarly seasonal isotopic variation of groundwater and field observations. The Xiegou well in the eastern Liupan Mountains is located in a relatively gentle slope associated with upper hills where the gullies or valleys around shallow groundwater sites are not developed. Unlike the Longchuan site, preferential groundwater recharge through the macro-pores and interface or slip surface are not very prevalent. The recharge mechanism may be more inclined to vertical infiltration and percolation like piston flow, which will greatly attenuate the seasonal variation of the stable isotopes in the groundwater for lower recharge rates and over a longer period of time. Although this needs to be demonstrated in the future by special systematic monitoring for precipitation-soil water-groundwater, the smaller seasonal variation of isotopes in groundwater at the Xiegou site suggests that preferential recharge like the Longchuan site may occur slightly.

5. CONCLUSIONS

(1) The different seasonal signatures of stable isotopes in most groundwater between winter and the summer period can be identified in high mountain-hills in the

western Loess Plateau. The groundwater shows more enriched deuterium and oxygen-18 isotopes and lower deuterium-excess values in the summer than that in the winter. This variation trend is roughly consistent with that of local precipitation stable isotopic characteristics. The scenario was strengthened with much more obvious fluctuation in the wet year 2013 than that of a typical year.

(2) Unlike in wide and flat loess tablelands in central and eastern Loess Plateau, local precipitation appears to be the only recharge source for groundwater in shallow loess aquifers. The recharge mechanism for loess groundwater in high mountain-hills is, in addition to common piston vertical infiltration, likely to include rapid preferential infiltration through larger sinkholes, fissures of slip surface, and also the interface of the loess layer and red clay or palaeo-soils, as a likely explanation. This plays an important role for groundwater recharge and resource replenishment. Seasonal recharge from local precipitation and mixing with old water existing aquifers sustain groundwater resources.

(3) Groundwater sources and flows within the shallow loess aquifers in high mountain-hills are controlled by heterogeneities and anisotropic conditions from the unique tectonics and topography, giving rise to preferential recharge conduits. Thus, any groundwater investigations in the future need to consider where these precipitation conduits for rapid infiltration exist rather than expecting all the precipitation to evaporate completely.

(4) Most groundwater is replenished after the heavy rainy season even after losses from extremely dry periods without recharge. However, land-use changes in recent decades may greatly impact local shallow groundwater.

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Appends: Caption of Figures and Tables:

Fig 1 Location of study area and sampling sites

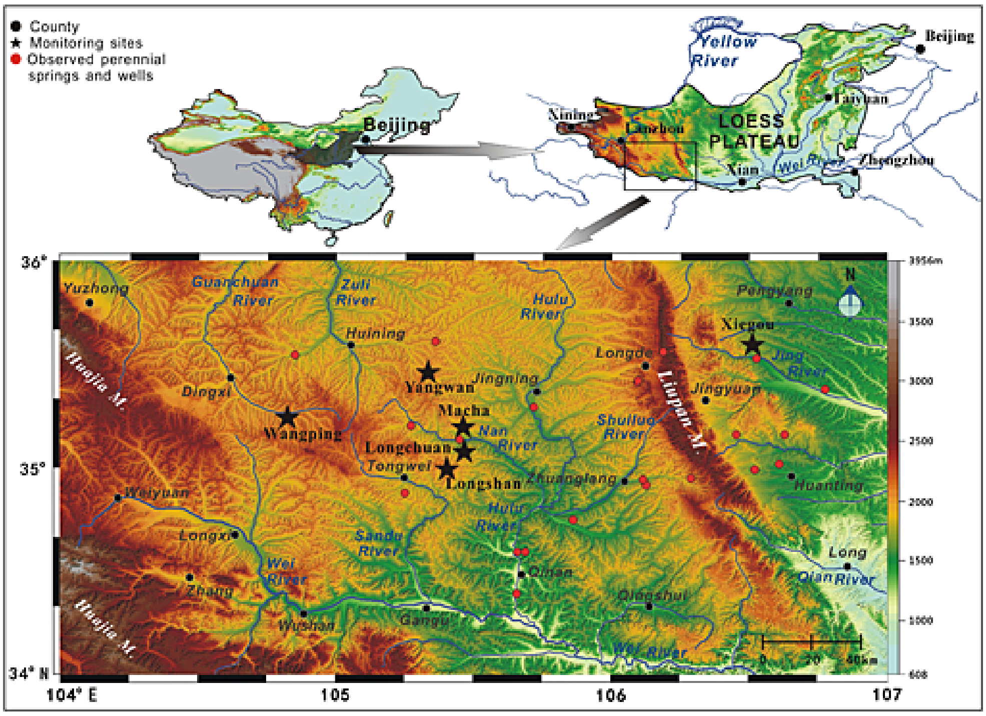
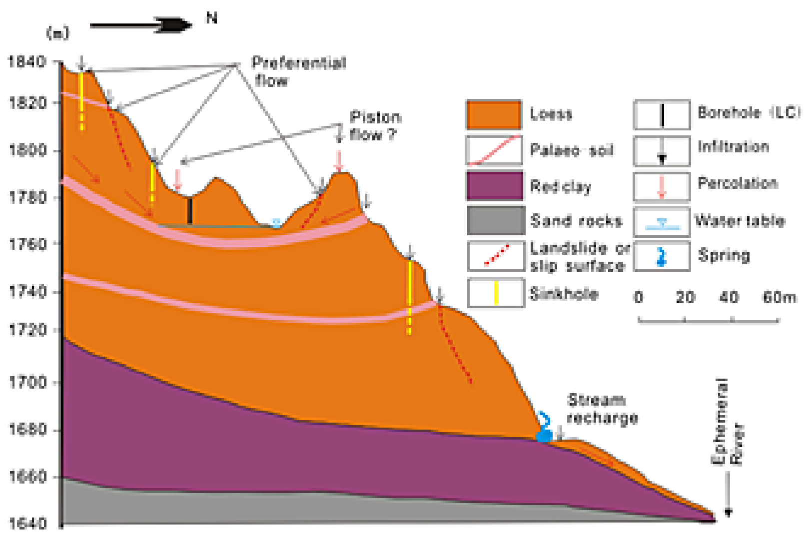


Fig 2 Conceptual map indicating the local precipitation recharge groundwater. Here, preferential recharge mode was identified by isotope data and field observation in this study. However, piston flow recharge mode was only presumed but need to be further assessed later (The sketch map was drawn from the profile of loess in Longchuan monitoring site).



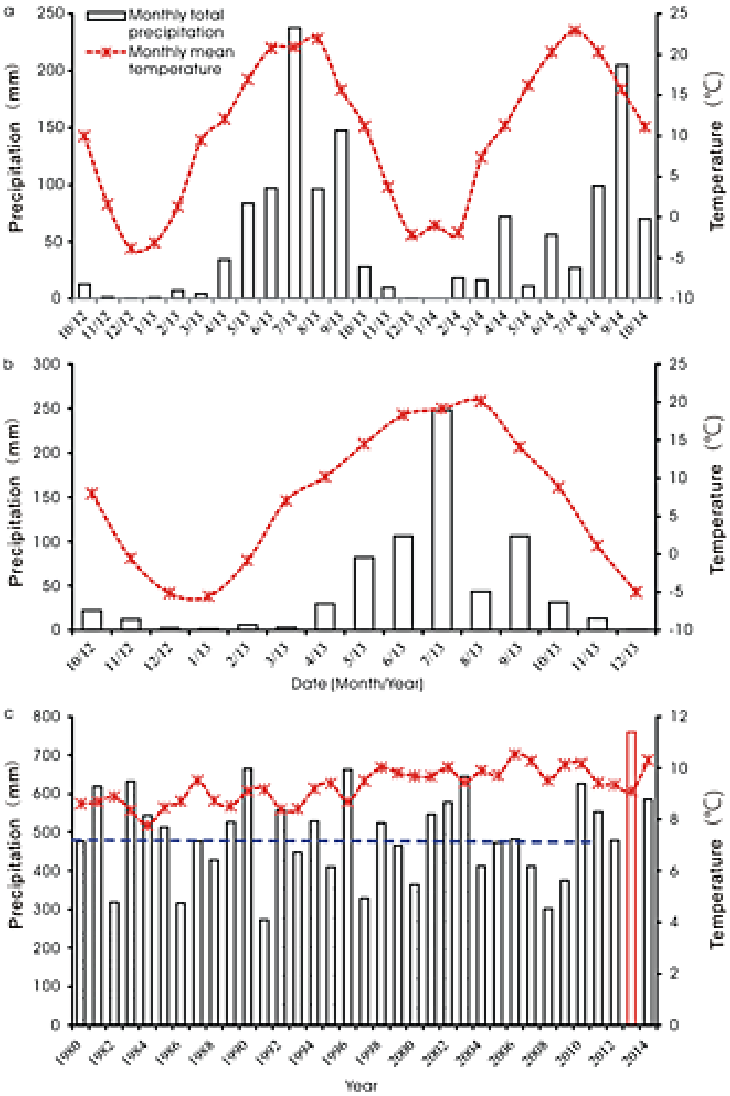


Fig 3 Variation of monthly total precipitation and mean temperature in two representative weather stations of (a) Pinging from 1/10/2012 to 31/10/2014, (b) Jingning from 1/10/2012 to 31/12/2013 and annual total precipitation and mean temperature in weather station of (c) Pingliang from 1980 to 2014 (The blue dash line refers to annual mean total precipitation in past 30 years from 1980 to 2010).

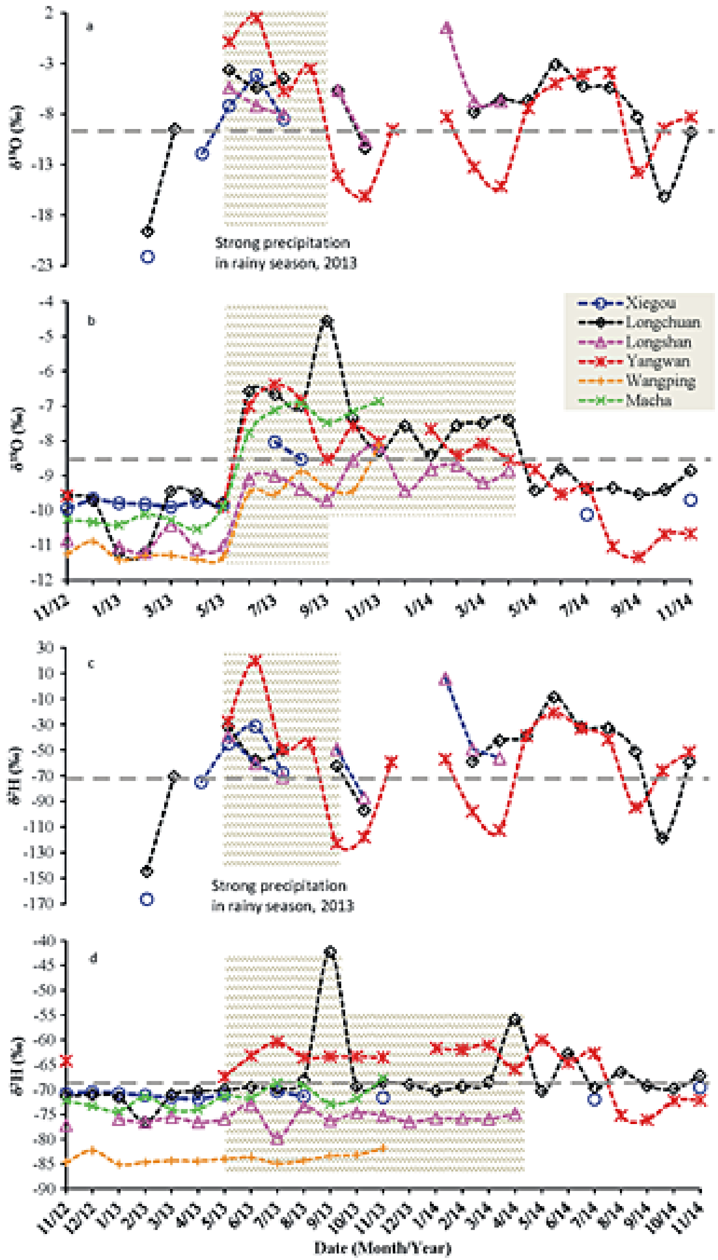
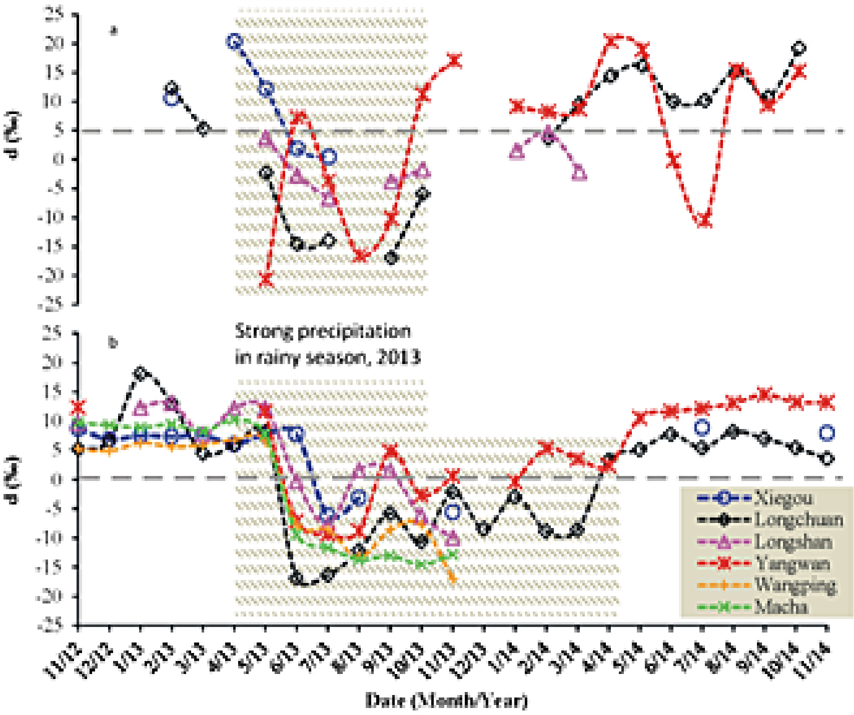


Fig 4 Monthly variations of $\delta^{18}O$ and $\delta^{2}H$ isotopes of (a and c) precipitation and (b and d) groundwater at sites of Xiegou, Longchuan, Longshan, Wangping (no precipitation samples), Macha (no precipitation samples) and Yangwan. The shadow filled area refers to strong precipitation in rainy season in 2013 and its possible effects on groundwater from May 2013 to April 2014 (Monthly data of precipitation calculated from average values of event precipitation in Table 2).

Fig 5 Monthly Variation of calculated deuterium excess of (a) precipitation and (b) groundwater at sites of Xiegou, Longchuan, Longshan, Wangping (no precipitation samples), Macha (no precipitation samples) and Yangwan. The shadow filled area refers to strong precipitation in rainy season in 2013 and its possible effects on groundwater from May 2013 to April 2014.



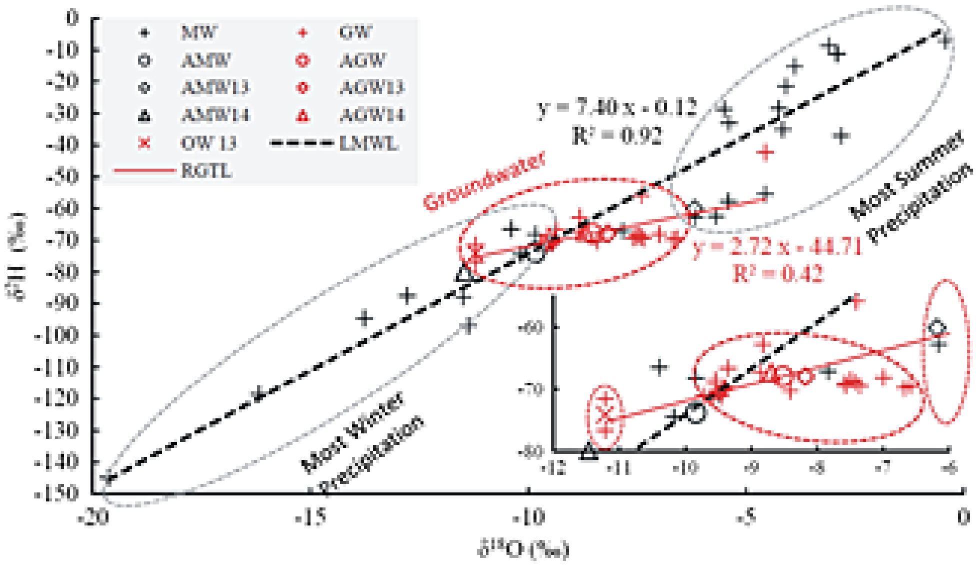


Fig 6 Diagrams of δ ^{2}H and δ ^{18}O for groundwater and precipitation samples for representative site at Longchuan. From the bottom-right plot, groundwater isotopic compositions mostly fall along a line between two end members: ① old water existing in aquifers from January to February 2013 with average values of δ^{18}O = -11.21‰ and δ^2H = -74.1‰ (OW13) and ② new recharged precipitation in 2013 with weighted average values of δ^{18}O = -6.19‰ and δ^2H = -60.2‰ (AMW13) (MW-Meteoric water; GW-Groundwater; AMW and AGW-Weighted average meteoric water and average groundwater during monitoring period from November 2012 to November 2014; AMW13 and AGW13-Weighted average meteoric water and average groundwater in 2013; AMW14 and AGW14-Weighted average meteoric water and average groundwater in 2014; OW13-Average groundwater in early 2013 from January to February; LMWL-local meteoric water line).

Table 1. Records of the basic characteristics of hydrology, geography and climate at main 6 monitoring sites in high mountain-hills in the Loess Plateau (Precipitation and atmosphere temperature refer to several years' annual average values from records of nearby weather station).

Sites	**Location**	**Elevation (m)**	**Land cover**	**Precipitation (mm/y)**	**Annual Mean Temp. (°C)**	**Sample types**	**Site description**
Longchuan	35°20′17.5"-105°27′34.8"	1767	Grass and crops	335	6.6	Monthly groundwater and event precipitation (>5mm)	The geomorphology is characterized by thick loess deposits with steeply incised valleys and rolling hills. All kinds of microtopography features exist such as vertical fissures, macro-pore, sinkholes, solution passages or sinks. At the top and halfway up the hills, the sinkholes that are generally over 1m in diameter and more than 5m in depth from surface can be widely observed. Small scale landslides in the higher place can also be universally found. Some springs distribute along depressions in the head of valleys. A drill about 10.5m can reach to loess aquifer and water table can rise to 1.5m. Generally groundwater table changes from 8m to 15m in depth from surface. Thick palaeo-soil under the loess aquifer may be acted as aquiclude to prevent groundwater percolate downward.
Longshan	35°14′55.6"-105°24′4.4"	2086	Grass, crops and trees	335	6.6	Monthly groundwater and event precipitation (>5mm)	The geomorphology is similar to Longchuan. Some wells and springs distribute along a gentle slope. Springs gush from head of valley. Wells are generally 15-20m in depth from surface and water tables fluctuate seasonally.
Yangwan	35°35′13.1″–105°19′50.4″	2092	Grass and crops	333	7.9	Monthly groundwater and event precipitation (>5	The geomorphology is similar to Longchuan. Wells and springs distribute from mountaintop to the head of valley. Wells are generally about 15 m in depth from surface in mountaintop, and their water tables

Table 1. Records of the basic characteristics of hydrology, geography and climate at main 6 monitoring sites in high mountain-hills in the Loess Plateau (Precipitation and atmosphere temperature refer to several years' annual average values from records of nearby weather station).

Sites	**Location**	**Elevation (m)**	**Land cover**	**Precipitation (mm/y)**	**Annual Mean Temp. (°C)**	**Sample types**	**Site description**
						mm)	rise in winter but decline in arid season.
Xiegou	35°41′21.0″–106°30′21.6″	1724	Grass and crops	450–700	8.5	Monthly groundwater and event precipitation (>5 mm)	The geomorphology shows relatively gently rolling topography. Aquifer of a well is 18 m in depth from surface with very rich groundwater, and water table fluctuates slightly all year round. Under the aquifer of loess is a thick red clay stratum. The elevation of the site is very high and almost to the top of hills.
Macha	35°23′34.8″–105°27′49.8″	1922	Grass, crops and trees	451	7.1	Monthly groundwater	Similar to Xiegou, many wells and springs distribute along a very gentle slope from loess mountaintop to head of valley. The shallow aquifer is about 15m in depth from surface and a set of light brown-red mudstone plays a role of aquiclude.
Wangping	35°25′53.9″–104°49′29.1″	2046	Grass	350–500	7	Monthly groundwater and event precipitation (>5 mm)	The geomorphology is similar to Longchuan, but the climate is very arid and water resources are very scarce. A well of 17 m in depth from surface was dug to the red clay in an intermingle zone of small valleys and ditches of a high loess hill. All valleys and ditches are always dry and run-off only occasionally occurs after heavy rains. The groundwater is slightly saline.

Table 2. The isotopic compositions (δ^2H, δ^{18}O and deuterium excess) of main event precipitations at Xiegou, Longchuan, Longshan and Yangwan monitoring sites in high mountain–hills in the Loess Plateau during 2-year monitoring period from November 2012 to November 2014

Date	**δ^2H**	**δ^{18}O**	**d**	***P***	**Date**	**δ^2H**	**δ^{18}O**	**d**	***P***	**Date**	**δ^2H**	**δ^{18}O**	**d**	***P***	**Date**	**δ^2H**	**δ^{18}O**	**d**	***P***
Xiegou					Longchuan					Longshan					Yangwan				
18 February 2013	−166.5	−22.13	10.5	6.5	2 February 2013	−144.8	−19.63	12.3	5	4 May 2013	−46.2	−6.86	8.7	5	7 May 2013	−27.8	−0.88	−20.7	23.5
29 April 2013	−75.1	−11.92	20.3	5	21 February 2013	−144.8	−19.62	12.2	6.5	5 May 2013	−13.3	−3.25	12.7	5	16 June 2013	19.3	1.51	7.3	5
26 May 2013	−45.5	−7.20	12.2	11.4	14 March 2013	−70.7	−9.49	5.3	5	8 May 2013	−64.3	−8.06	0.2	5	8 July 2013	−49.6	−5.73	−3.7	63.2
20 June 2013	−31.4	−4.16	1.9	73.9	1/5/13	−28.7	−5.50	15.3	5	15 May 2013	−8.1	−1.29	2.2	23.5	23 August 2013	−44.7	−3.52	−16.5	31.4
8 July 2013	−76.1	−8.80	−5.7	63.2	4 May 2013	−35.0	−4.16	−1.8	5	24 May 2013	−65.1	−7.51	−5.1	5.7	7 September 2013	−122.7	−14.07	−10.2	5.9
26 July 2013	−59.5	−8.25	6.5	7.5	14 May 2013	−7.1	−0.42	−3.8	16	1 June 2013	−62.3	−7.57	−1.7	5	28 October 2013	−117.9	−16.13	11.2	9.6
					25 May 2013	−55.5	−4.56	−19.1	11.4	9 June 2013	−62.7	−7.44	−3.1	5	23 November 2013	−59.4	−9.55	17.0	6.8
					20 June 2013	−57.9	−5.41	−14.6	73.9	20 June 2013	−56.2	−6.60	−3.4	73.9	10 January 2014	−57.0	−8.27	9.2	5
					1 July 2013	−37.1	−2.82	−14.5	14	8 July 2013	−71.8	−8.22	−6.0	63.2	14 February 2014	−97.9	−13.25	8.2	18

Table 2. The isotopic compositions (δ^2H, $\delta^{18}O$ and deuterium excess) of main event precipitations at Xiegou, Longchuan, Longshan and Yangwan monitoring sites in high mountain–hills in the Loess Plateau during 2-year monitoring period from November 2012 to November 2014

Date	δ^2H	$\delta^{18}O$	d	*P*	Date	δ^2H	$\delta^{18}O$	d	*P*	Date	δ^2H	$\delta^{18}O$	d	*P*	Date	δ^2H	$\delta^{18}O$	d	*P*
					8 July 2013	−62.8	−6.16	−13.5	63.2	28 July 2013	−70.6	−7.91	−7.3	5	8 March 2014	−112.6	−15.15	8.7	16
					4 September 2013	−62.5	−5.69	−17.0	11.1	18 September 2013	−49.2	−5.67	−3.8	12.7	2 April 2014	−23.6	−5.85	23.2	20
					3 October 2013	−96.9	−11.37	−6.0	12.5	16 October 2013	−65.8	−7.82	−3.2	12.5	18 April 2014	−54.5	−9.00	17.5	25
					1 February 2014	−88.0	−11.49	3.9	10	29 October 2013	−108.5	−13.53	−0.3	9.6	13 May 2014	−20.9	−4.97	18.9	11
					7 February 2014	−21.5	−4.09	11.2	5	6 January 2014	6.0	0.57	1.5	5	9 June 2014	−8.5	0.23	−10.4	30
					19 February 2014	−67.1	−7.83	−4.4	6	8 February 2014	−31.3	−4.67	6.1	5	28 June 2014	−57.4	−8.40	9.9	14
					7 March 2014	−74.4	−10.17	6.9	16	16 February 2014	−67.1	−8.80	3.3	6	22 July 2014	−41.6	−3.89	−10.5	27
					30 March 2014	−11.1	−2.93	12.3	20	2 April 2014	−56.2	−6.75	−2.2	20	10 August 2014	−94.7	−13.76	15.4	99
					18 April 2014	−66.4	−10.39	16.7	25						8 September 2014	−66.1	−9.43	9.4	205
					25 April	−11.2	−2.90	12.0	22						12	−40.6	−7.94	22.9	8.5

Table 2. The isotopic compositions (δ^2H, $\delta^{18}O$ and deuterium excess) of main event precipitations at Xiegou, Longchuan, Longshan and Yangwan monitoring sites in high mountain–hills in the Loess Plateau during 2-year monitoring period from November 2012 to November 2014

Date	δ^2H	$\delta^{18}O$	d	*P*	Date	δ^2H	$\delta^{18}O$	d	*P*	Date	δ^2H	$\delta^{18}O$	d	*P*	Date	δ^2H	$\delta^{18}O$	d	*P*
					2014										October 2014				
					9 May 2014	−8.7	−3.10	16.1	11						28 October 2014	−73.2	−11.30	17.2	5
					13 June 2014	0.5	−1.65	13.7	30										
					19 June 2014	−68.1	−9.84	10.6	12										
					28 June 2014	−28.4	−4.25	5.5	14										
					21 July 2014	−33.0	−5.39	10.1	27										
					10 August 2014	−94.7	−13.76	15.4	99										
					23 September 2014	−118.6	−16.17	10.7	205										
					1 October 2014	−15.2	−3.88	15.9	8.5										
					30 October 2014	−87.7	−12.78	14.5	5										
SD	43.6	5.7	8.2			39.4	5.1	11.3			26.8	3.1	5.2			36.5	5.0	13.1	
AMW					AMW	−73.8	−9.84	4.9		AMW	−56.1	−6.72	−2.4		AMW	−54.3	−6.89	0.9	

Table 2. The isotopic compositions (δ^2H, $\delta^{18}O$ and deuterium excess) of main event precipitations at Xiegou, Longchuan, Longshan and Yangwan monitoring sites in high mountain–hills in the Loess Plateau during 2-year monitoring period from November 2012 to November 2014

Date	δ^2H	δ^{18}O	d	*P*	Date	δ^2H	δ^{18}O	d	*P*	Date	δ^2H	δ^{18}O	d	*P*	Date	δ^2H	δ^{18}O	d	*P*
AMW13	−57.0	−7.23	0.8		AMW13	−60.2	−6.19	−10.7		AMW13	−57.7	−6.86	−2.8		AMW13	−54.3	−5.45	−10.7	
AMW14					AMW14	−79.8	−11.46	11.8		AMW14					AMW14	−55.4	−8.50	12.6	
AW-13	−126.8	−17.69	14.8		AW-13	−122.3	−16.56	10.1		AW-13					AW-13				
AW-14					AW-14	−50.8	−7.46	8.9		AW-14	−45.9	−5.79	0.4		AW-14	−70.6	−10.66	14.6	
AS-13	−51.9	−6.46	−0.2		AS-13	−52.7	−5.00	−12.7		AS-13	−54.9	−6.50	−2.9		AS-13	−49.6	−4.40	−14.5	
AS-14					AS-14	−90.2	−12.77	12.0		AS-14					AS-14	−51.3	−7.60	9.6	

P, amount of precipitation; SD, standard deviation; AMW, annual average value (from November 2012 to November 2014); AMW13, annual average value in 2013; AMW14, annual average value in 2014; AW-13, average value in winter half year (from November 2012 to April 2013); AW-14, average value in winter half year (from November 2013 to April 2014); AS-13, average value in summer half year (from May to September 2013); AS-14, average value in summer half year (from May to September 2014). Here, all average values are weighted means by amount of larger precipitation events. The amount of precipitation data is from adjacent Pingliang Weather Station

Table 3. The isotopic compositions (δ^2H, $\delta^{18}O$ and deuterium excess) of monthly groundwater at main six monitoring sites (Xiegou, Longchuan, Longshan and Yangwan) in high mountain–hills in the Loess Plateau during 2-year monitoring period from November 2012 to November 2014

DateM/Y	Xiegou			Longchuan			Longshan			Yangwan			Wangping			Macha		
	δ^2H/‰	^{18}O/‰	d/‰	δ^2H/‰	^{18}O/‰	d/‰	δ^2H/‰	^{18}O/‰	d/‰	δ^2H/‰	^{18}O/‰	d/‰	δ^2H/‰	^{18}O/‰	d/‰	δ^2H/‰	^{18}O/‰	d/‰
11/2012	−70.9	−9.95	8.7	−71.4	−9.58	5.2	−77.2	−10.85	9.6	−64.3	−9.58	12.3	−84.8	−11.25	5.2	−72.3	−10.26	9.8
12/2012	−70.5	−9.67	6.9	−71.1	−9.72	6.7				−68.2	−9.66	9.1	−82.3	−10.90	4.9	−73.4	−10.33	9.3
01/2013	−70.8	−9.79	7.5	−71.6	−11.21	18.1	−76.0	−11.04	12.3				−85.1	−11.42	6.3	−74.4	−10.41	8.9
02/2013	−71.2	−9.82	7.4	−76.6	−11.21	13.1	−76.6	−11.21	13.1				−84.7	−11.29	5.7	−71.5	−10.12	9.4
03/2013	−71.6	−9.90	7.6	−71.2	−9.46	4.5	−75.7	−10.43	7.7				−84.4	−11.29	5.9	−74.0	−10.28	8.2
04/2013	−71.9	−9.74	6.1	−70.4	−9.54	5.9	−76.6	−11.10	12.2				−84.4	−11.40	6.8	−74.0	−10.54	10.3
05/2013	−71.0	−9.85	7.8	−68.5	−9.54	8.1	−75.9	−11.02	12.2	−57.6	−8.90	13.7	−84.0	−11.34	6.7	−71.4	−9.89	7.7
06/2013				−69.5	−6.59	−16.8	−73.1	−9.10	−0.3	−63.3	−7.01	−7.2	−83.7	−9.49	−7.8	−71.6	−7.77	−9.5
07/2013	−70.4	−8.04	−6.1	−69.8	−6.67	−16.4	−79.8	−9.01	−7.7	−60.5	−6.39	−9.4	−84.9	−9.54	−8.6	−68.7	−7.13	−11.6
08/2013	−71.4	−8.53	−3.2	−68.1	−6.99	−12.2	−73.5	−9.38	1.5	−63.6	−6.84	−8.8	−84.3	−8.88	−13.3	−69.2	−6.93	−13.7
09/2013				−42.3	−4.56	−5.8	−76.2	−9.71	1.4	−63.4	−8.53	4.8	−83.4	−9.34	−8.6	−72.9	−7.48	−13.1
10/2013				−69.4	−7.35	−10.6	−74.7	−8.56	−6.2	−63.4	−7.58	−2.7	−83.1	−9.43	−7.7	−71.8	−7.16	−14.5
11/2013	−71.7	−8.26	−5.6	−68.9	−7.42	−9.5	−75.3	−8.16	−10.0	−63.6	−8.02	0.6	−81.9	−8.11	−17.0	−67.8	−6.87	−12.8
12/2013				−69.1	−7.57	−8.5	−76.5	−9.43	−1.1									
01/2014				−70.3	−8.41	−3.0	−75.8	−8.82	−5.3	−61.7	−7.67	−0.4						
02/2014				−69.4	−7.57	−8.9	−75.9	−8.70	−6.3	−62.0	−8.41	5.3						
03/2014				−68.5	−7.49	−8.6	−76.0	−9.21	−2.3	−61.1	−8.07	3.5						
04/2014				−55.9	−7.41	3.3	−74.9	−8.86	−4.0	−65.9	−8.54	2.4						
05/2014				−70.3	−9.43	5.1				−60.1	−8.83	10.6						
06/2014				−62.8	−8.82	7.7				−64.6	−9.53	11.6						
07/2014	−72.0	−10.12	8.9	−69.7	−9.39	5.4				−62.7	−9.36	12.2						
08/2014				−66.6	−9.35	8.2				−75.2	−11.04	13.1						

Table 3. The isotopic compositions (δ^2H, $\delta^{18}O$ and deuterium excess) of monthly groundwater at main six monitoring sites (Xiegou, Longchuan, Longshan and Yangwan) in high mountain–hills in the Loess Plateau during 2-year monitoring period from November 2012 to November 2014

DateM/Y	**Xiegou**			**Longchuan**			**Longshan**			**Yangwan**			**Wangping**			**Macha**		
	δ^2H/‰	**^{18}O/‰**	**d/‰**	**δ^2H/‰**	**^{18}O/‰**	**d/‰**	**δ^2H/‰**	**^{18}O/‰**	**d/‰**	**δ^2H/‰**	**^{18}O/‰**	**d/‰**	**δ^2H/‰**	**^{18}O/‰**	**d/‰**	**δ^2H/‰**	**^{18}O/‰**	**d/‰**
09/2014				−69.3	−9.54	7.0				−76.1	−11.33	14.5						
10/2014				−69.9	−9.41	5.4				−72.3	−10.69	13.2						
11/2014	−69.7	−9.70	8.0	−67.3	−8.86	3.6				−72.2	−10.67	13.2						
SD	0.7	0.69	5.5	6.3	1.50	9.3	1.4	1.00	7.8	5.0	1.37	7.8	1.0	1.13	8.5	2.0	1.54	10.9
AGW	−71.1	−9.45	4.5	−67.9	−8.52	0.3	−75.9	−9.68	1.6	−65.1	−8.83	5.6	−83.9	−10.28	−1.7	−71.8	−8.86	−0.9
AGW13	−71.3	−9.24	2.7	−67.9	−8.18	−2.5	−75.8	−9.84	2.9	−62.2	−7.61	−1.3	−84.0	−10.14	−2.9	−71.6	−8.60	−2.8
AGW14	−70.8	−9.91	8.4	−67.3	−8.70	2.3				−66.7	−9.47	9.0						
AWGW13	−71.1	−9.81	7.4	−72.0	−10.12	8.9	−76.4	−10.93	11.0	−66.3	−9.62	10.7	−84.3	−11.26	5.8	−73.3	−10.32	9.3
AWGW14				−67.4	−7.60	−6.5	−75.6	−8.82	−5.0	−63.0	−8.05	1.4						
ASGW13	−71.0	−8.81	−0.5	−63.6	−6.87	−8.6	−75.7	−9.64	1.4	−61.7	−7.53	−1.4	−84.1	−9.72	−6.3	−70.7	−7.84	−8.0
ASGW14	−72.0	−10.12	8.9	−67.7	−9.30	6.7				−67.8	−10.02	12.4						

SD, standard deviation; AGW, annual average value (from November 2012 to November 2014); AGW13, annual average value in 2013; AGW14, annual average value in 2014; AWGW13, average value in winter half year (from November 2012 to April 2013); AWGW14, average value in winter half year (from November 2013 to April 2014); ASGW13, average value in summer half year (from May to September 2013); ASGW14, average value in summer half year (from May to September 2014)